METROLOGY

• Metrology: Science of measurement

• Measurement: Comparison of a specimen to a standard, within some agreed upon reference frame.

• Measurements & Standards important to technology & commerce!

SCIENCE SUBCOMMITTEE HOLDS HEARING ON STANDARDS AND TRADE (2005): The House Science Committee's Subcommittee on Environment, Technology, and Standards held a hearing this week on the potential for standards to be used as barriers to trade. The hearing focused specifically on China and Europe.

In his opening statement, Subcommittee Chairman Vernon Ehlers (R-MI) noted the importance of standards and said "standards play a powerful role in domestic and international markets. If a standard achieves broad acceptance in a market, it may lead to the abandonment of technologies supported by alternative standards and the domination of a market by a specific technology." Ehlers said trade barriers can arise with standards when nations set domestic standards that are different from those, which foreign manufacturers would have normally used. This increases the cost of doing business in that country and is a barrier to trade because a company would have to manufacture two sets of standards if it wanted to trade there.

• All countries maintain Standards:
  o USA: National Institute of Standards & Technology (NIST)
  o France: Bureau of Weights & Measures (Sevres)
Terms

• **Accuracy**
  - Degree of conformity to a standard
  - Degree of agreement of the measured dimension with its true magnitude.

• **Precision**
  - Degree of refinement to which a measurement can be stated, e.g., number of digits.
  - Degree to which an instrument gives repeated measurement of the same standard.

• **Resolution**
  - Smallest dimension that can be read on an instrument.
  - Smallest programmable step a machine can make during point to point motion.

• **Repeatability:**
  - Error between a number of successive attempts to move a machine to the same position.
  - Ability to do the same thing over & over.
• **Static Range**: Physical limit on range of values that can be measured accurately and repeatedly.

• **Dynamic Range**: Frequency range/bandwidth over which measurements are accurate and repeatable.

• **Calibration**: Adjusting or setting an instrument to give readings accurate within a reference standard.

• **Sensitivity**: Smallest difference in dimension that an instrument can distinguish or detect.

• **Stability**: Instrument’s ability to maintain calibration.
MEASUREMENTS

• Measurement: Comparison of a specimen to a standard, within some agreed upon reference frame.
  
  o A successful measurement must maintain (i.e., apply controls to) specimen, standard, and a stable reference frame.
  o All measurements based on standard.
  o Maintenance of standards & reference frame critical to any measurement

• Measurement process: Compare specimen to standard. Errors can arise from variations in
  
  o specimen
  o standard
  o reference frame
  o comparison process

• When measuring one variable, must hold others fixed:
  
  o Example: temperature measurement, fix vibration, force, etc.
  o Often results in “vicious cycle” of fixing variables

• Improvement of one standard demands improvement of others. Controls on measurements link standards.
SI Measurement System

7 Basic quantities

- Length
- Mass
- Temperature
- Time
- Luminous intensity
- Amount of substance (moles)
- Electric current
• Measurements important to manufacturing:
  o Dimensions & Length
  o Time
  o Shape: straightness, roundness, flatness
  o Temperature
  o Force
  o Torque
  o Velocity
  o Flows
  o Position
  o Displacement
  o Angles
  o Pressure
  o Surface roughness
  o Surface waviness
  o Power
Length, Position, Displacement & Dimensions

• Original standard: meter bar, distance between marks
  Conditions: maintain temperature & loads
  Comment: time measurement (with clock or pendulum) depends on length.
  *Length most fundamental quantity.*

• 1960 standard: wavelength of krypton gas (86 isotope), green light, wavelength ~ 0.5 µm
  Conditions: maintain frequency (time)
  Comment: length measurement depends on time measurement.
  *Time most fundamental quantity.*

• Modern standard: distance light travels in vacuum during 1/299,792,458 seconds
  Conditions: maintain time & vacuum
  *Time most fundamental quantity.*

QUESTION: What controls must be placed on these standards?
Length, Position, Displacement & Dimensions

Measured with

- Scale: ruler with precision markings
- Micrometer caliper:
  - Jaws with threads (precision ≈ 0.1 mm)
  - With vernier (precision ≈ 0.01 mm)
- Interferometer
  - Count interference fringes
  - Precision: ~1/8 wavelength (≈ 0.1 µm)
  - Very high dynamic bandwidth (> 100 kHz)
- Capacitance gauges
  - Capacity of probe
  - Precision: ~ 0.1 to 1 µm
  - 40 kHz bandwidth
- Linear Variable Differential Transducer (LVDT)
  - Pairs of coils in push/pull
  - Precise & accurate (~10 µm)
  - Low bandwidth (10 to 100 Hz)
- Gauge blocks
  - Accurately dimensioned to ± 0.0001 mm
  - Stack together for other dimensions
- Others: potentiometers
- Metrology: checking for instrument errors

- Flawed standard, but “stable” reference frame
- Gauge errors by Reversal of Instrument
- Example: Square

![Diagram of ideal and real carpenters squares]

**Question:** How to detect small error with imperfect instrument?

**Answer:** Reverse the instrument, errors double
Example: Level

- Bubble at highest height tube indicates horizontal

- Flawed level on inclined surface: bubble centered

- Reverse the level on inclined surface: bubble not centered
  - Errors from surface & instrument
  - Forward: $\theta_f = \theta_{\text{instr}} + \theta_{\text{surf}}$
  - Reverse: $\theta_r = -\theta_{\text{instr}} + \theta_{\text{surf}}$
  - Difference: $\theta_t = \theta_f - \theta_r = 2\theta_{\text{instr}}$

Difference: doubles instrument error $\theta_{\text{instr}}$ & removes specimen’s bias $\theta_{\text{surf}}$
Example: Spindle axes of rotation

- Test and reference spindles have wobble

  - Forward: Green driven by Purple
  - Reversed: Purple driven by Green
Error Budgets

List errors from all sources

Estimate errors

Ensure sum of errors within acceptable limit: “budget” errors to each source

Most precision engineering errors (displacements) from temperature fluctuations and variations
○ Time

Measure requires repetitive (periodic) event

• Original standard: pendulum period
  Conditions: maintain pendulum length
  Comment: time measurement derives from length. 
  Length most fundamental quantity.

• 1960 standard: atomic clock
  Method: Excite Cesium atoms to higher energy state, 
  observe frequency (~ 9,192,631,770 Hz) of radiation 
  Comment: length measurement derives from time. 
  Time most fundamental quantity.

• Future standard: optical clock
  Method: Excite (Mercury? Strontium? Ytterbium?) 
  atoms with laser. Tune laser frequency to atom. 
  Comments:
    ○ frequencies $10^5$ higher
    ○ Improved measurement of fundamental time 
      bootstraps entire system of standards!
Physicists' work on clocks may redefine each second

By Malcolm Ritter
ASSOCIATED PRESS

NEW YORK — Some physicists are creating a revolution in the arcane world of ultra-precise clocks. And among them is a researcher who has trouble getting anywhere on time.

"I do tend to be a little bit late," Jim Bergquist, 58, said. "Quite a bit late."

Of course, the time he focuses on professionally is far removed from the world of dinner dates and planes to catch.

Bergquist, who is with the National Institute of Standards and Technology in Boulder, Colo., works with extremely accurate devices that rely on the behavior of atoms to measure time. In fact, he is working on what could be the world's most accurate timepiece.

In Bergquist's world, a 10-billionth of a second is just too long a time between ticks of a clock. And it really makes a difference that a clock in mile-high Denver ticks faster than another at sea level. (Time itself passes more quickly when gravity is reduced.)

In his line of work, the focus isn't on producing the highly accurate clocks that report the official time of the world. It's on producing the even-more-precise devices that are used to judge the accuracy of those clocks. Such devices are also used to sharpen interplanetary navigation.

Ultimately, they should also help reveal fundamental secrets of the universe and perhaps help in sending secure information over the Internet.

Bergquist and others have demystified a way to make the devices, through an approach he figures will eventually replace the technology that has reigned for 50 years.

The new way is so accurate that Bergquist thinks it will probably make scientists redefine what a second is.

This summer, Bergquist and colleagues published a head-to-head comparison of the nation's standard ultra-precise clock with the new technology he and others have been pursuing.

The current standard clock will neither gain nor lose a second in 70 million years. The new clock pushes those figures out to 400 million years.

Bergquist figures that with further development, the new technology will become at least 100 times as accurate as the standard clock could ever be.

The secret of the new clock? It "ticks" faster than the standard one. And the more ticks per unit of time, the more precisely that unit can be measured.

Think of trying to time a 100-yard dash: If your clock ticks only once per second, Bergquist said, it will be hard to determine the winner if the race comes down to a hundredth of a second. But a stopwatch that ticks every one-thousandth of a second will do the job.

In fact, Bergquist's device is more like a stopwatch than a clock. It is turned on only intermittently to measure particular intervals of time, rather than being left on continuously to reveal the time of day.

The new clock technology might not only displace the old, but it might also force a revision in what physicists regard as the definition of one second. The current definition, like the ultra-precise clocks now in use, is based on microwaves and the behavior of a cesium atom.

The nucleus of a cesium atom switches back and forth between two physical states when it is hit with microwave radiation of a particular frequency. That frequency is the "tick" of current clocks. One second, to physicists, is 9,192,631,770 such ticks.

The new "optical" clocks instead hit an atom with a laser beam, finely tuned to a certain frequency. Laser "ticks" come about 100,000 times faster and thus could become the new basis for the definition of a second.

That won't happen right away. Bergquist figures it will take five or 10 years for scientists to decide on the best kind of atom to use in the heart of the optical clocks.

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Measurement of Shapes

- Compare (exemplar) standard to specimen
- Measure out-of-shape
- Important shapes
  - straightness (out-of-straightness)
  - flatness (out-of-flat)
  - roundness (out-of-roundness)
Straightness (out-of-straightness)

• Based on distance

• Measure: deviation of specimen from standard

• Original standard: bar (straight edge), carefully machined “straight”. Compare to specimen:

• Modern standard: laser beam

• Practical (shop) measurement of straightness

- table must be flat
- critical: alignment of elements
Flatness (out-of-flatness)

- Involves surface

- Original standard: Precision “flat” surface, e.g., table

- Measure: deviation of specimen from standard

- Shop measurement: gap between specimen & “flat” table (standard)
• Optical measurement: gap between specimen & optical flat (standard)

• Optical path difference:

\[ \text{OPD} = \int_{\text{light path}} (n_1 - n_2) \cdot ds \]

- \( n_i = \frac{v_i}{c} \) refractive index
- \( v_i \) speed of light in media (flat)
- \( c \) speed of light in vacuum

• path difference generates fringes
• fringes indicate degree of out-of-flatness
• Geometry: \( Z(x,y) = 0.5 \text{OPD cos } \theta \)
Commercial optical flat on surface

- Alternating light & dark fringe bands
- Distance between dark bands indicates OPD change of 1 wavelength
Roundness (out-of-roundness)

- Standards: Precision “circle,” “cylinder,” “sphere”
- Measure: deviation of specimen from standard

**Measurement 1**

- Full rotation: total indicator reading = max - min

**Measurement 2:** part stationary, platform rotates
Angular Measurements

Protractor

Inclinometers
Pendulum
Bubble Level of fluid: $10^{-4}$ degrees

Encoders: light source, photodiode & 2 discs with slits
Disc 1: stationary, with 1 slit
Disc 2: multiple spaced slits, fixed to rotor
When slits align, pulse @ photodiode
Count pulses for amount of angular rotation
Blocks & Sine bar

Stack precision blocks to produce $L, \delta h$

Synthesize angle $\theta$ from $\sin \theta = \frac{\delta h}{L}$
Temperature

Infra-red and/or visible emissions

- **Thermocouple**: bi-metallic junction, produces voltage dependent on junction temperature (Peltier effect)
- Machining temperature difficult to measure
  - Tool obstructs measurement (in the way)
  - Cutting tool/workpiece used as thermocouple

Force

- Strain gauges
- Load cells
- Piezo-electric

Velocity

- Tachometers
- Encoders

Power
Tolerances

Acceptable limits on part variations that will not affect function, safety, assembly, etc.

Too small => higher costs
Too large => compromises function

Interchangeability

Part dimension between:

**Bilateral limits**: part dimensions between

Nominal value – lower tolerance
Nominal value + upper tolerance

**Symmetric limits**: nominal ± tolerance

**Statistical tolerancing**

Measure part dimension \( x \)
Interpret \( x \) as random variable with density \( f(x) \)

Permits stacking of tolerances
Can estimate probability of achieving a total tolerance for multiple parts assembled into a component